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Falconbridge Limited

To: Dr. K.G. Davis, CANMET, Scientific Authority

# INFLUENCE OF CASTING VARIABLES AND STRUCTURE ON MECHANICAL PROPERTIES OF HK40 STATIC CASTINGS

**FINAL REPORT: PHASES II, III and IV**
**DSS CONTRACT SERIAL NO. 15SQ.23440-3-9131**

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MICROMEDIA

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## SUMMARY

This project was sponsored by CANMET to improve the technology used by Canadian foundries to produce high alloy castings. An investigation was completed to determine the influence of casting conditions and structure on the mechanical properties of HK40 sand castings.

Room temperature tensile data for aged and as-cast specimens show that both ultimate strength and % elongation tend to increase with finer dendrite structures. Stress rupture ductility increases as grain size increases.

Contrary to published claims, rupture strength and hot tensile strength were found to be insensitive to a broad range of grain sizes and dendrite spacings.

The most significant commercial opportunity to come from this work is the ability to maximize ductility using coarse grain castings with fine dendrite structures. A work plan is outlined to demonstrate the significance of this development using commercially produced centrifugal castings.

## INTRODUCTION

This project is sponsored by CANMET to improve the technology used by Canadian foundries to produce cast heat resistant alloys (1,2). The first phase of the project examined the influence of pouring temperature and section size on solidification rates and structure of HK40 sand castings (3). This report summarizes the effect of casting conditions and structure on the mechanical properties of HK40. Detailed progress reports have been issued to record the data and the statistical analyses (4 to 18).

## SAMPLE PREPARATION AND TEST PROCEDURE

Material for the project was produced in the form of step castings of HK40 using induction melts of virgin charge materials. Initial heats were cast into $CO_2$ bonded sand moulds with section thicknesses of 15 mm, 43 mm and 85 mm. Heats were cast at temperatures in the range from 1450°C to 1735°C. In-mould thermocouples were used to determine the solidification time and cooling rate in each of the three section thicknesses. Samples produced in this manner were sectioned for macroscopic determination of grain size and microscopic measurement of secondary dendrite arm spacing. The method of sample preparation and the metallographic results are fully described in reference 3.

Similar procedures were used to produce a series of step castings for mechanical property evaluation. For these castings, the in-mould thermocouples were removed. A total of 15 heats were produced using casting temperatures of 1470°C, 1600°C and 1730°C. This resulted in sections with a grain size variation from 1.1 mm to 6.6 mm and secondary dendrite arm spacings for 0.044 mm to 0.11 mm, as shown in Table I.

The composition of the 15 heats was carefully controlled (6), producing the following ranges:

| | |
|---|---|
| Carbon | 0.36 - 0.41% |
| Nickel | 19.7 - 20.1% |
| Chromium | 24.2 - 25.0% |
| Manganese | 0.63 - 0.73% |
| Silicon | 1.0 - 1.2% |
| Sulphur | 0.002 - 0.004% |

Test bars for all types of mechanical testing were produced in the form of threaded samples with a 0.252" x 1.0" gauge as per ASTM A370. The sample locations within the step casting are illustrated in figure 1. The test bar axis was perpendicular to the riser axis for the 15 mm and 43 mm sections, but because of the casting geometry was parallel to the riser axis in the 85 mm sections. Test bars in the 43 mm section were located entirely in the bottom half of the step only. In the 85 mm section, bars were machined from both the edge and centre due to macrostructure differences.

Room temperature tensile tests in the as-cast condition and after aging at 760°C for 48 hours were conducted to the requirements of ASTM specification E8. These tests were conducted in triplicate at each variable.

Hot tensile tests of as-cast material at 871°C and 982°C were made to the requirements of ASTM E21, again using triplicate samples.

Stress rupture tests were performed to the requirements of ASTM E139 at 871°C with an applied stress of 7.8 ksi and at 982°C with 4.80 ksi. These tests were also conducted in triplicate. Furthermore, at each temperature, the same three stress-rupture machines were used for tests of each variable.

## RESULTS

Complete results and analysis of the data from each phase of the project are given in the Progress Reports (3,10,13,16,17,18). The data was treated graphically and by single and multiple regression analyses.

Table I summarizes the effect of variations in pouring temperature and section size on the solidification time, the grain size and the secondary dendrite arm spacing. The casting variables resulted in solidification times varying from 65 to 1225 seconds, producing grain sizes of 1.1 to 6.6 mm and arm spacings from 0.044 to 0.11 mm. The grain size and arm spacings shown in Table I were determined from the shoulders of the fractured aged tensile samples.

The effect of pouring temperature and section size on the mechanical properties is summarized in Table II. By using the sample code, these data can be related to the casting conditions and structure measurements shown in Table I.

## DISCUSSION

### Metallography

The secondary dendrite arm spacings given in Table I are from the aged tensile specimens (16), but these numbers are in excellent agreement with measurements taken during Phase I (3). It should be recognized that the carbide morphology also varied as the cooling rate varied, as shown by the example (5) in figure 2. Hence mechanical properties which correlate with dendrite arm spacing may in fact be controlled by carbide morphology.

The grain size measurements given in Table I are in disagreement with grain width measurements reported in Phase I. These data are based on area measurements of the grains in the aged tensile specimens (16), whereas the previous data were linear intercept measurements from different locations in the step castings (3). Figure 3 is a series of sketches which illustrate the range of macrostructures which were evaluated.

**Room Temperature Tensile Data**

Ultimate tensile strength of both as-cast and aged specimens tended to decrease as the secondary dendrite arm spacing increased. Figure 4 shows the multiple regression fit for several grains sizes (10, 17). Since dendrite arm spacing is controlled by solidification time, which is in turn controlled by the cooling modulus and pouring temperature, it should not be surprising that some correlation was also found with these variables. Figure 5 shows the influence of cooling modulus and pouring temperature on ultimate tensile strength of as-cast specimens.

Yield strength was not clearly related to the casting conditions or structures studied. However as shown in Table II, the yield strength did not vary widely despite the range of structures evaluated.

Percent elongation data showed considerable scatter and Table II shows that the 80% confidence intervals were ± 29 relative percent around the averages. Despite the scatter some correlation was found with the secondary dendrite arm spacing. Figure 6 shows that % elongation tends to decrease as the secondary dendrite arm spacing increases. Regression analysis attributed 49% of the observed variance for aged specimens, and 17% of the observed variance for as-cast speciments to dendrite arm spacing. Thin section castings had remarkably good aged ductility which is very important for thermal shock resistance and repair weldability. Fractographic examination showed an interdendritic mode of fracture for almost all tensile specimens. For large dendrites, the interdendritic carbides become much larger and blockier as was shown in figure 2. These data suggest that finely distributed carbides are perferable to enhance both as-cast and aged ductility.

For as cast specimens there was a loss in % elongation associated with pouring at 1600°C, which is shown in figure 7. Aged specimens were not influenced to the same extent, hence % elongation was more clearly related to dendrite arm spacing for aged specimens. No structural feature or defect could be found to explain the loss in ductility at intermediate pouring temperature.

**Hot Tensile Data**

As shown in Table I, ultimate and yield strengths were found to be insensitive to the wide range of casting conditions and structures studied. The range in strength values was narrow, being:

(a) ultimate strength at 871°C : 24 to 27 ksi
(b) yield strength at 871°C : 16 to 19 ksi
(c) ultimate strength at 982°C : 16 to 19 ksi
(d) yield strength at 982°C : 10 to 12 ksi

Most of the variance in these averages is attributed to scatter in the replicate measurements.

For tensile tests at 871°C, % elongation tended to decrease with increasing dendrite arm spacing, solidification time and cooling modulus. Correlation coefficients were of the order of 0.5. For a given section size, there was loss in ductility when samples were poured at 1600°C. Figure 8 shows the effects of pouring temperature and cooling modulus on % elongation. Neither of these trends were clearly shown for tensile data at 982°C. However these trends were very consistent with the trends shown for room temperature tests on as-cast specimens.

**Stress Rupture Data**

The stress-rupture tests resulted in a relatively wide range of both rupture life and fracture ductility at both test temperatures. Analysis of the data is confounded by the scatter in the replicate tests, where the 80% confidence interval around the mean rupture life is ± 35%. For fracture ductility this range is ± 35% to ± 38% of the mean (18).

Regression analysis showed the strongest correlations between life at 871°C were with modulus squared and solidification time. However, even these correlations were weak with values of <0.4. Regression analyses of these single variables only expanded 13 to 15% of the variance. Only when all variables were considered: modulus squared, pouring temperature, solidification time, arm spacing and grain size, could 77% of the variance be explained.

Multiple regression analysis of rupture life at 982°C could only explain 12% of the observed variance.

The lives of samples from thin sections poured at 1730°C and tested at 871°C were statistically different and may be due to the sample gauge consisting of bi-crystals or single crystals. However, this same material tested at 982°C was not statistically different.

The differences in rupture life shown in Table II could not be explained terms of the variations in casting conditions and resultant structural features. However most of these differences are not statistically significant (18).

The significance of the apparently large variations in rupture life is clarified if viewed in terms of extrapolated long term rupture stresses. Figure 9 shows a Larson-Miller versus rupture stress plot of published raw data for HK40 (19). From this plot it may be seen that the average 10,000 hour rupture life at 843°C is 5.0 ksi in a range from 4.05 to 5.95 ksi. Converting the rupture life values in Table II to Larson Miller parameters plotted against stress shows their mean 10,000 hour life at 843°C to be 5.06 ksi with a standard deviation of 0.163 ksi. These differences in rupture strength have little technical significance.

The range of commercial rupture lives, therefore, appears to be very large when compared with the extrapolated valves from this study. It is not, however, unreasonable to assume that the commercial data is based on samples with a much larger compositional variance and possibly similar structural variance. This

strongly suggests the variance in extrapolated long term strength is more related to changes in composition than structural features.

Variations in fracture ductility, as measured by elongation and reduction of area, were primarily related to grain size with a weaker contribution from arm spacing. Figure 10 shows elongation increasing with increasing grain size and with decreasing arm spacing. Similarly reduction of area increased with increasing pouring temperature, as shown in figure 11.

Thus while the overall rupture strength of HK40 appears to be relatively insensitive to structural variations, these structural changes do have a more pronounced effect upon ductility.

## CONCLUSIONS

1. Room temperature tensile data on both as-cast and aged specimens show increasing ultimate strength and % elongation as the secondary dendrite arm spacing decreases. This can be achieved by shortening the solidification time, either by reducing the section size or by increasing the cooling rate.

2. Despite the range of grain sizes and dendrite sizes studied, the following mechanical properties were not significantly altered:

   (a) Room temperature yield strength, as cast
   (b) Room temperature yeild strength, aged
   (c) Ultimate strength at 871°C
   (d) Ultimate strength at 982°C
   (e) Yield strength at 871°C
   (f) Yield strength at 982°C
   (g) Rupture life at 871°C and 7.8 ksi
   (h) Rupture life at 982°C and 4.8 ksi

3. The relative insensitivity of extrapolated long term rupture strength to structural variations strongly suggests that the large variance in commercial data is primarily related to differences in chemical composition.

4. In several cases, low ductility was associated with pouring at 1600°C, rather than 1570°C or 1730°C. No structural change or defect was found to be associated with these low values of % elongation.

5. Stress rupture ductility increases with increasing grain size.

## RECOMMENDATION

The most significant commercial opportunity to come from this work is the ability to maximize ductility using coarse grain castings with fine dendrite structures. Resistance to low cycle thermal fatigue, particularly in ethylene

pyrolysis coils, is being recognized as of equal or greater significance than high temperature strength. Demonstration that a resistance to thermal embrittlement can be controlled at the casting stage has significant commercial advantages. This is particularly relevant to the Canadian Petrochemical industry where high technology off-shore foundries enjoy a disproportionate market share relative to Canadian suppliers.

It is recommended that Phase V of this project be modified to develop this opportunity and to verify the major findings from Phases II to IV. Specifically it is recommended that the project be directed to the properties of commercially produced centrifugal castings.

The work plan would include:

1. Production of centrifugal and static castings at two superheats to demonstrage ductility maximization both at room temperature and after short and long term aging.

2. Effect of maximizing ductility upon repair welding (i.e. after long term aging) to be investigated.

3. Demonstrate maximization of ductility at high temperature in both tensile and stress rupture tests.

4. Investigate the effect of carburization upon the aged ductility at ambient and elevated temperatures, with respect to structural control.

R.J. Dawson

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(16) Memo: R. Gilpin/R.J. Dawson, "Check Metallography on Test Specimens", February 27, 1986

(17) Memo: R. Gilpin/R.J. Dawson, "Statistical Analysis of Dendrite Arm Spacing and Grain Width Measurments", March 14, 1986

(18) Memo: R.J. Dawson/R. Gilpin, "Detailed Record of Statistical and Graphical Analyses - Phase II - Stress Rupture Testing", September 29, 1986

(19) "Petrochemical Capability and Experience", Fahramet Steel Castings, Indusmin Division of Falconbridge, May 1986

TABLE I: SUMMARY OF CASTING CONDITIONS AND STRUCTURAL MEASUREMENTS (16)

| Sample Code | Pouring Temp. (°C) | Sample Location | Solidification Time (Sec) | Grain Size (mm) | Dendrite Arm Spacing (mm) |
|---|---|---|---|---|---|
| A1 | 1470 | Thick-Middle | 725 | 3.0 | 0.081 |
| A2 | 1470 | Thick-Edge | 725 | 3.1 | 0.087 |
| A3 | 1470 | Medium | 265 | 1.7 | 0.066 |
| A4 | 1470 | Thin | 65 | 1.1 | 0.044 |
| B1 | 1600 | Thick-Middle | 1030 | 2.1 | 0.11 |
| B2 | 1600 | Thick-Edge | 1030 | 4.1 | 0.11 |
| B3 | 1600 | Medium | 435 | 4.4 | 0.091 |
| B4 | 1600 | Thin | 130 | 2.3 | 0.051 |
| C1 | 1730 | Thick-Middle | 1225 | 4.7 | 0.11 |
| C2 | 1730 | Thick-Edge | 1225 | 4.0 | 0.10 |
| C3 | 1730 | Medium | 550 | 6.6 | 0.087 |
| C4 | 1730 | Thin | 175 | 3.5 | 0.063 |

TABLE II: THE EFFECT OF POURING TEMPERATURE AND SECTION SIZE ON AVERAGE MECHANICAL PROPERTIES OF HK40 ALLOY

| | R.T. Tensile - Cast | | | R.T. Tensile - Aged | | | 871°C - Tensile | | | 982°C - Tensile | | | Rupture - 871°C | | | Rupture - 982°C | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample Code | UTS ksi | YS ksi | El. % | UTS ksi | YS ksi | El. % | UTS ksi | YS ksi | El. % | UTS ksi | YS ksi | El. % | Life Hrs. | El. % | RA % | Life Hrs. | El. % | RA % |
| A1 | 65 | 34 | 17 | 72 | 42 | 4 | 27 | 17 | 38 | 16 | 10 | 55 | - | - | - | - | - | - |
| A2 | 64 | 35 | 17 | 69 | 43 | 3 | 25 | 17 | 30 | 19 | 12 | 33 | 230 | 14 | 19 | 173 | 17 | 29 |
| A3 | 67 | 36 | 18 | 75 | 43 | 4 | 27 | 17 | 33 | 18 | 11 | 43 | 208 | 15 | 16 | 112 | 17 | 24 |
| A4 | 77 | 38 | 24 | 84 | 44 | 10 | 27 | 16 | 39 | 18 | 11 | 49 | 211 | 9 | 11 | 123 | 8 | 13 |
| B1 | 57 | 38 | 10 | 68 | 42 | 3 | 27 | 17 | 27 | 18 | 11 | 37 | - | - | - | - | - | - |
| B2 | 60 | 38 | 11 | 68 | 41 | 4 | 27 | 18 | 24 | 17 | 11 | 38 | 164 | 20 | 27 | 185 | 12 | 29 |
| B3 | 64 | 37 | 14 | 68 | 44 | 4 | 26 | 18 | 31 | 17 | 10 | 40 | 247 | 16 | 31 | 122 | 25 | 39 |
| B4 | 74 | 37 | 16 | 84 | 43 | 8 | 26 | 18 | 36 | 19 | 12 | 36 | 286 | 12 | 15 | 195 | 17 | 34 |
| C1 | 59 | 35 | 17 | 68 | 43 | 4 | 24 | 19 | 31 | 18 | 12 | 41 | - | - | - | - | - | - |
| C2 | 59 | 36 | 21 | 68 | 44 | 3 | 27 | 17 | 31 | 18 | 11 | 49 | 329 | 11 | 34 | 148 | (5) | 36 |
| C3 | 67 | 36 | 22 | 76 | 46 | 9 | 25 | 18 | 38 | 17 | 10 | 40 | 157 | 33 | 56 | 155 | 36 | 66 |
| C4 | 72 | 37 | 24 | 81 | 48 | 11 | 25 | 18 | 42 | 18 | 12 | 44 | 423 | 21 | 21 | 156 | 26 | 50 |
| 80% C.I. | ±5% | ±4% | ±29% | ±5% | ±4% | ±29% | ±4% | ±5% | ±13% | ±4% | ±5% | ±13% | ±35% | ±35% | ±38% | ±35% | ±35% | ±38% |

Notes: (i) Section Key:
A = 1470°C Pour Temp.
B = 1600°C Pour Temp.
C = 1730°C Pour Temp.
1 = Thick (85 mm) - Middle
2 = Thick (85 mm) - Edge
3 = Medium (43 mm)
4 = Thin (15 mm)

(ii) 80% C.I. = Confidence interval expressed as a relative percentage of the average value.

(iii) Stress for rupture tests at 871°C = 7.80 ksi

(iv) Stress for rupture tests at 982°C = 4.80 ksi

UTS = Ultimate Tensile Strength
YS = Yield Strength
%El = % Elongation
%RA = % Reduction in Area
R.T.= Room Temperature

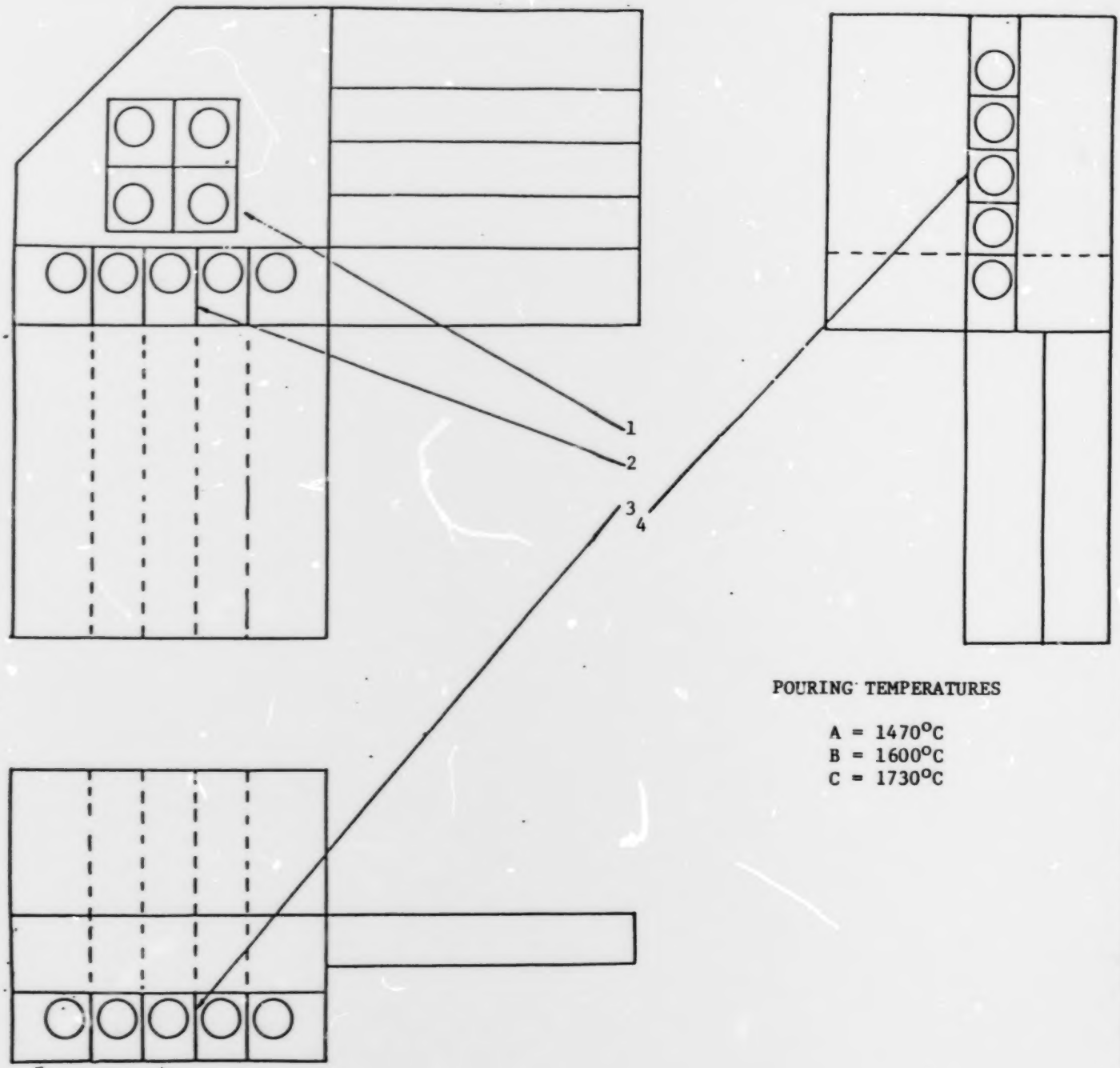



FIGURE 1: LOCATION OF MECHANICAL TEST SPECIMENS IN STEP CASTINGS

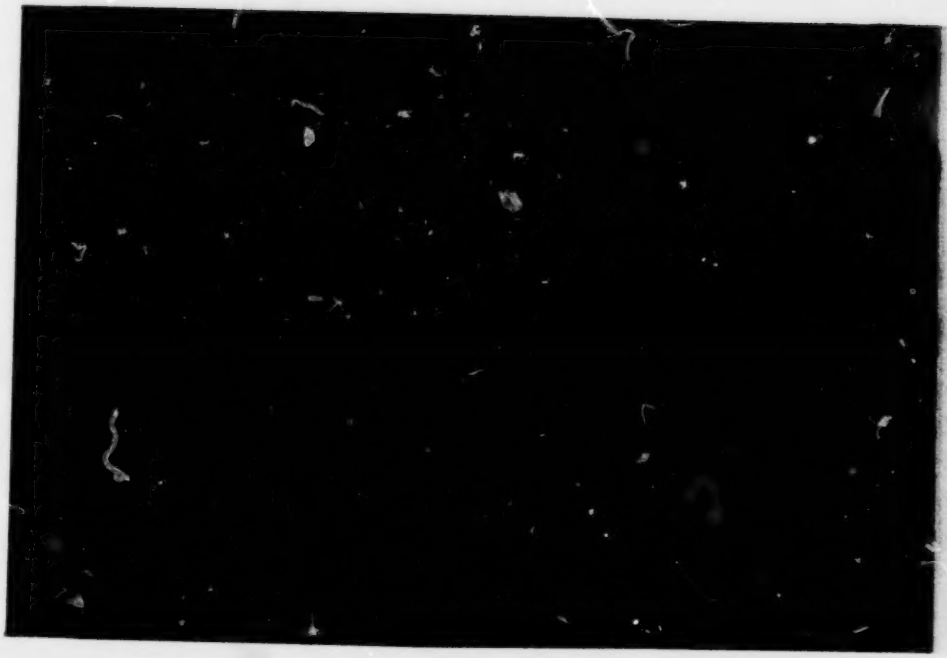
Also letter code for samples

(a)

(b)

FIGURE 2: CARBIDE MORPHOLOGIES FOR THREE COOLING RATES (S) x500

(a) 3°C/sec (b) 1.5°C/sec (c) 0.2°C/sec



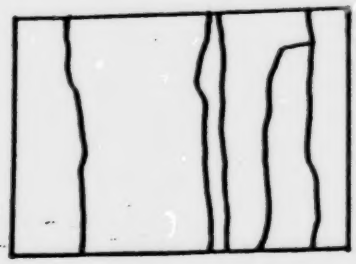
(c)

FIGURE 2: CARBIDE MORPHOLOGIES FOR THREE COOLING RATES (5) x500

(a) 3°C/sec (b) 1.5°C/sec (c) 0.2°C/sec

GRAIN CONFIGURATION:

Equiaxed - All Samples
Similar to Figure 1A, Sections 1 & 2,
Different from Figures 2A & 3A,
Sections 1 & 2 (Phase I Report) in
that no columnar features are apparent.

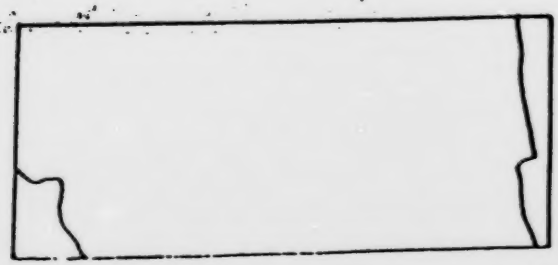


GRAIN CONFIGURATION:

Columnar, with grains perpendicular
to the gauge length.
Similar to Figures 1A, 2A, 3A.
Sections 3 & 5. (Phase I Report)

GRAIN CONFIGURATION:

Coarse, Very Blocky.
Similar to Figures 5A to 8A,
Sections 1 & 2 (Phase I Report)



GRAIN CONFIGURATION:

Very Coarse. Single grain in one
case. Very similar to Figure 9A,
Sections 1 & 2 (Phase I Report)

FIGURE 3: RANGE OF MACROSTRUCTURES OBSERVED IN AGED TENSILE SPECIMENS (16)

FIGURE 4

INFLUENCE OF DENDRITE ARM SPACING AND GRAIN WIDTH ON ULTIMATE TENSILE STRENGTH OF AS-CAST SPECIMENS

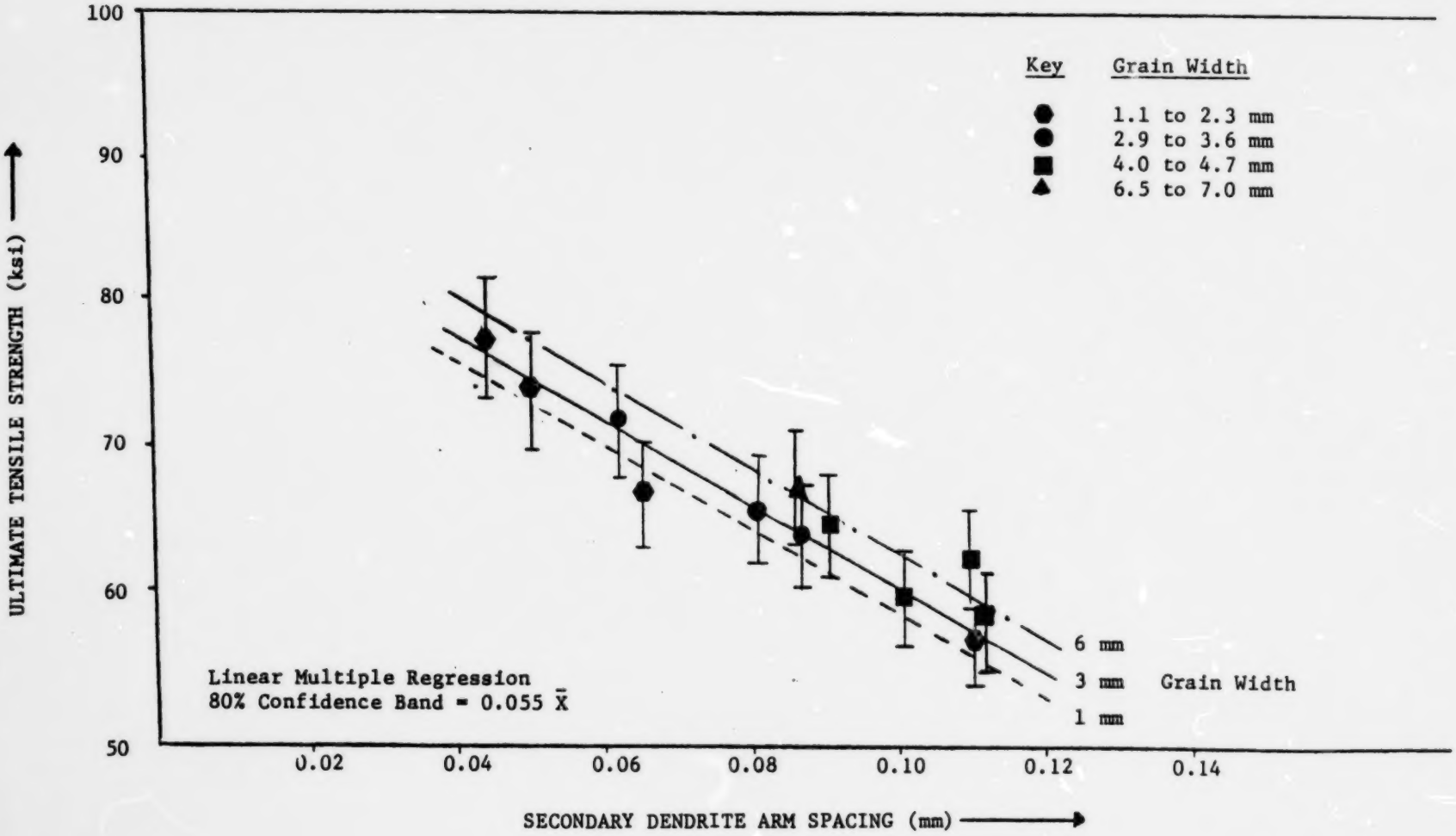


FIGURE 5 INFLUENCE OF MODULUS AND POURING TEMPERATURE ON ULTIMATE TENSILE STRENGTH AS-CAST SPECIMENS

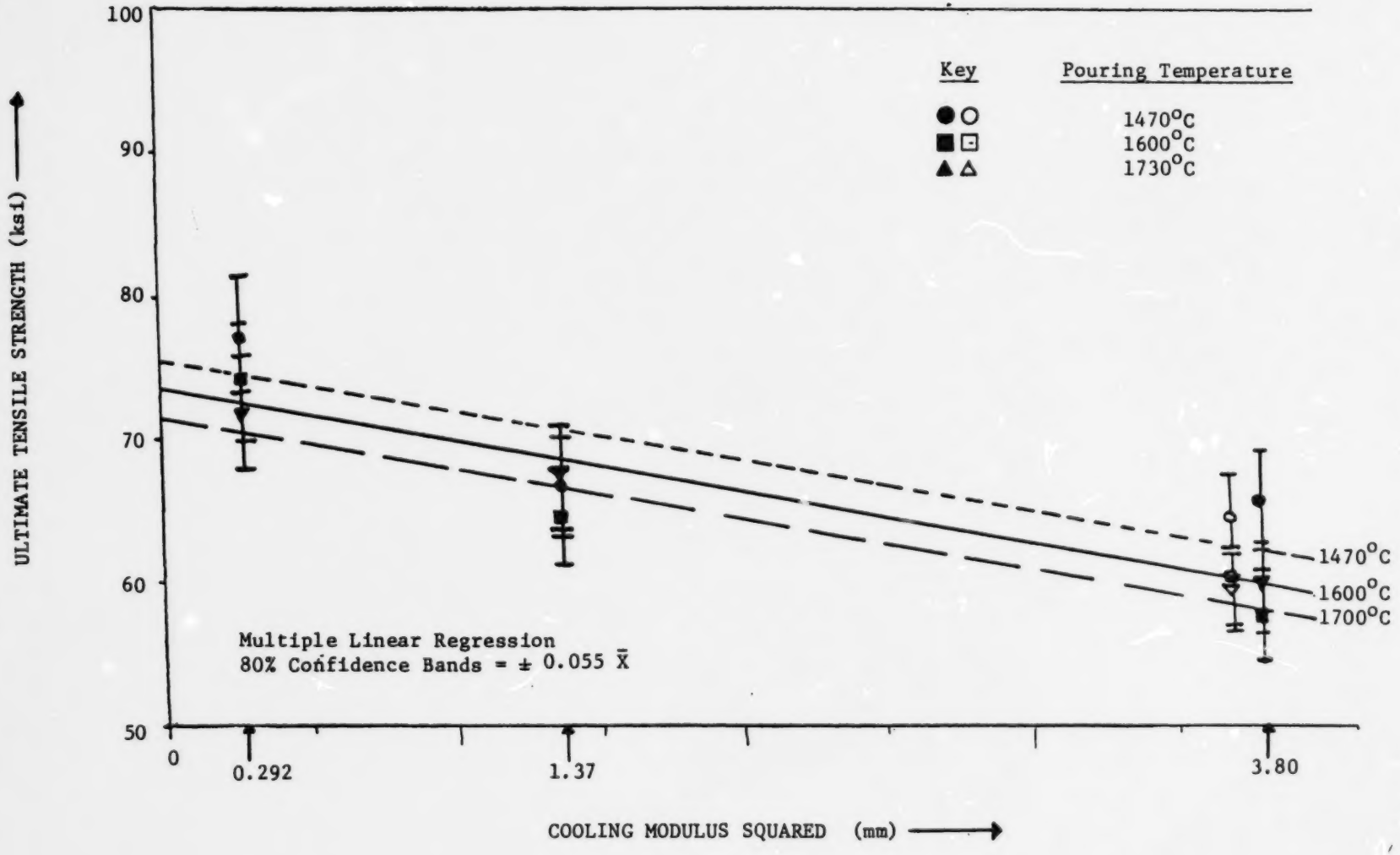


FIGURE 6

INFLUENCE OF DENDRITE ARM SPACING AND % ELONGATION OF AGED SPECIMENS

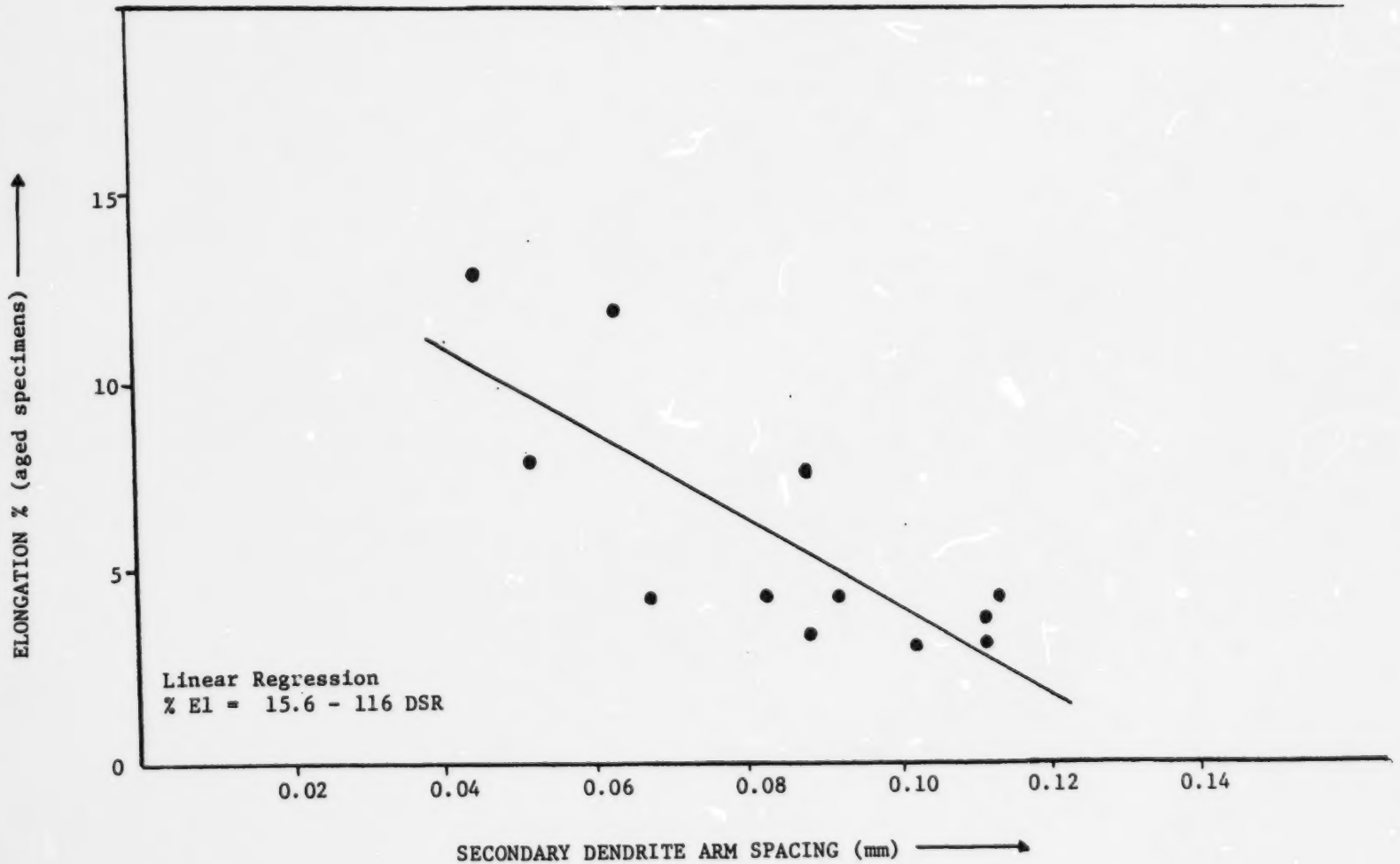


FIGURE 7

INFLUENCE OF POURING TEMPERATURE AND COOLING MODULUS SQUARED ON % ELONGATION OF AS-CAST SPECIMENS

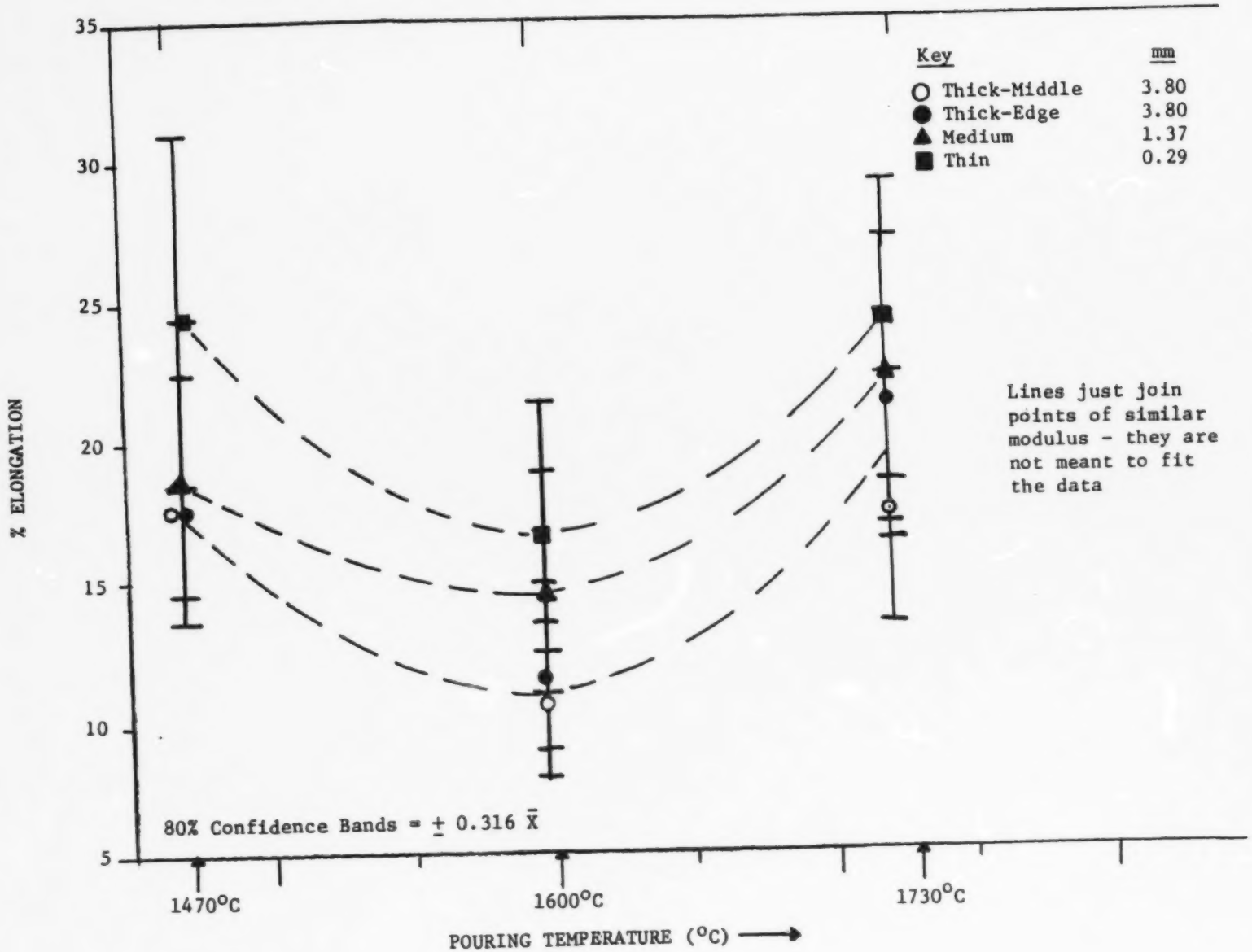
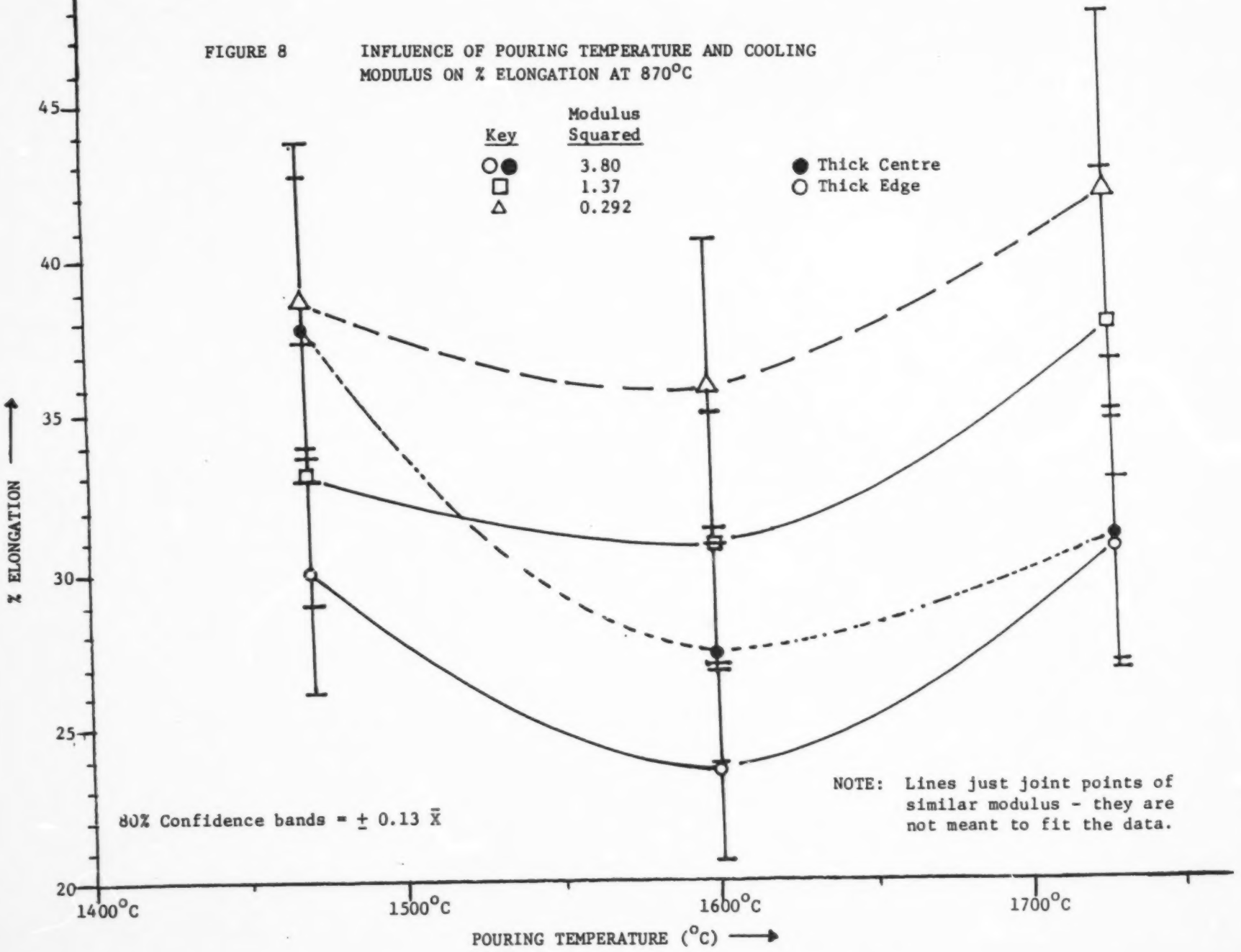


FIGURE 8 INFLUENCE OF POURING TEMPERATURE AND COOLING MODULUS ON % ELONGATION AT 870°C



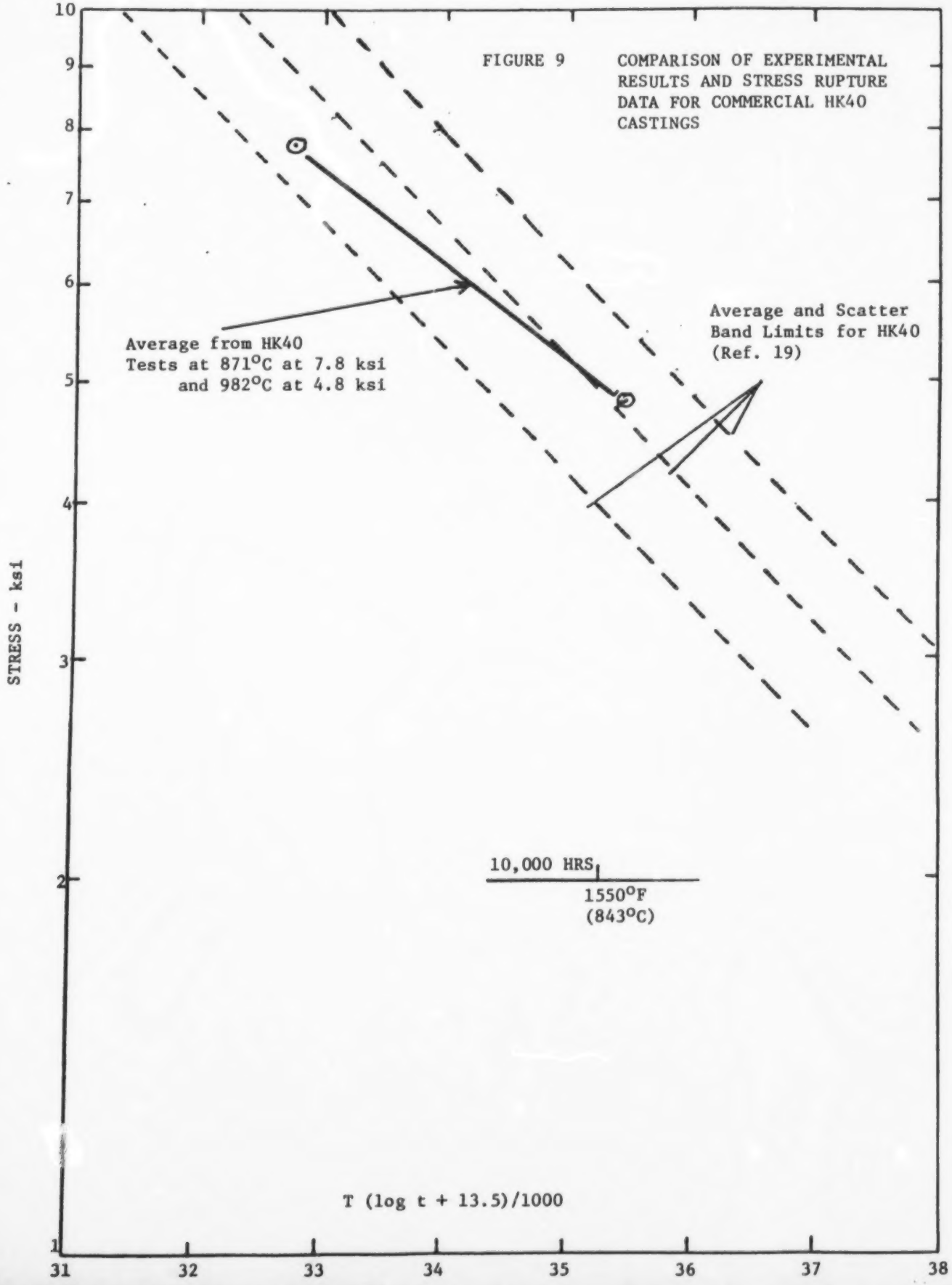



FIGURE 9 COMPARISON OF EXPERIMENTAL RESULTS AND STRESS RUPTURE DATA FOR COMMERCIAL HK40 CASTINGS

FIGURE 10

EFFECT OF GRAIN WIDTH & DENDRITE ARM SPACING ON ELONGATION OF SAMPLES STRESS-RUPTURE TESTED AT 871°C, 7.80 ksi

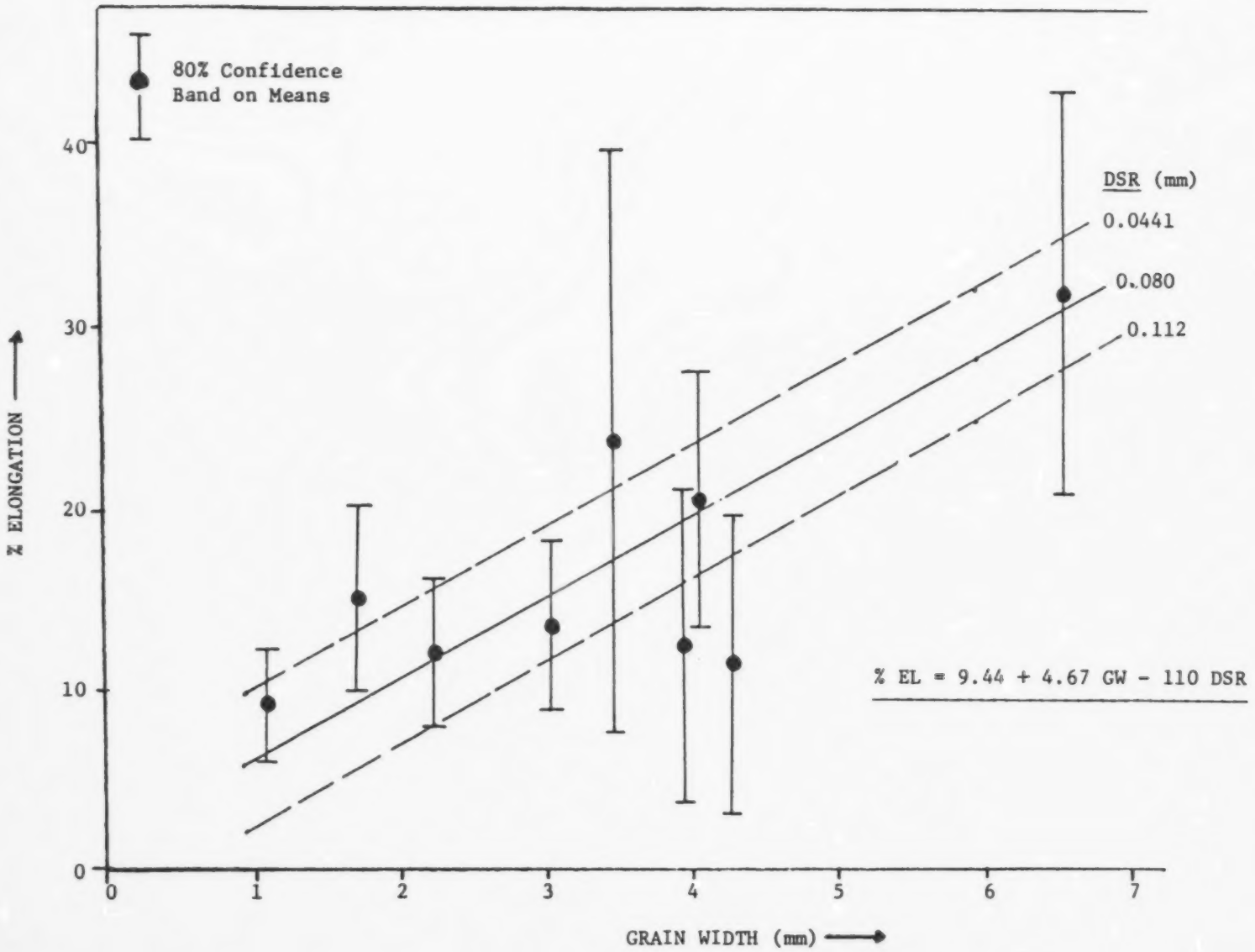


FIGURE 11

EFFECT OF POURING TEMPERATURE ON ELONGATION OF SAMPLES STRESS-RUPTURE TESTED AT 871°C, 7.80 ksi